

(19) World Intellectual Property Organization
International Bureau



(43) International Publication Date
19 June 2003 (19.06.2003)

PCT

(10) International Publication Number
WO 03/050472 A1

(51) International Patent Classification⁷: **G01B 9/00**

(21) International Application Number: PCT/US02/39526

(22) International Filing Date: 9 December 2002 (09.12.2002)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
10/014,037 10 December 2001 (10.12.2001) US

(71) Applicant: **OPHTHONIX, INC.** [US/US]; 10455 Pacific Center Court, San Diego, CA 92121 (US).

(72) Inventor: **HORWITZ, Larry, S.**; 146 12th Street, Seal Beach, CA 90740 (US).

(74) Agent: **REISMAN, Joseph, M.**; Knobbe, Martens, Olson & Bear, LLP, 2040 Main Street, 14th Floor, Irvine, CA 92614 (US).

(81) Designated States (*national*): AE, AG, AL, AM, AT (utility model), AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ (utility model), CZ, DE (utility model), DE, DK (utility model), DK, DM, DZ, EC, EE (utility model), EE, ES, FI (utility model), FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, OM, PH, PL, PT, RO, RU, SC, SD, SE, SG, SK (utility model), SK, SL, TJ, TM, TN, TR, TT, TZ, UA, UG, UZ, VC, VN, YU, ZA, ZM, ZW.

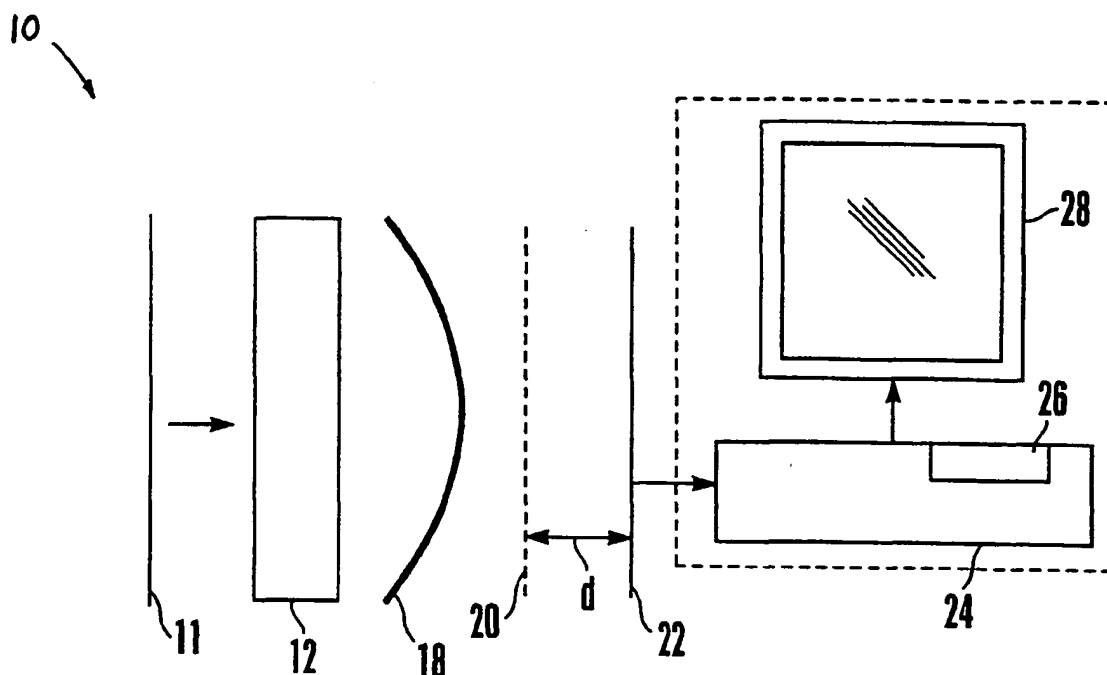
(84) Designated States (*regional*): ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE, SI, SK, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:

— with international search report

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

(54) Title: **SYSTEM AND METHOD FOR WAVEFRONT MEASUREMENT**



(57) Abstract: A wavefront measuring system and method for detecting phase aberrations in wavefronts that are reflected, transmitted through internally reflected within objects sought to be measured which includes placing a reticle (20) in the path of a return beam from the object (12), and placing a detector (22) at a diffraction pattern self-imaging plane relative to the reticle (20). A set of known polynomials is fitted to the wavefront phase gradient to obtain polynomial coefficients that describe aberrations in the object.

SYSTEMS AND METHODS FOR WAVEFRONT MEASUREMENT

FIELD OF THE INVENTION

[0001] The present invention relates generally to systems and methods for
5 measuring phase characteristics of electromagnetic wavefronts.

BACKGROUND

[0002] Measuring how a wavefront deviates from being perfectly diffraction-
limited has many applications. As non-limiting examples, measuring deviations, also
referred to as "aberrations", in a wavefront produced by an optical system, such as a
10 telescope, can reveal manufacturing flaws in the system, since many optical systems, to
function as best as is possible, preferably produce diffraction-limited wavefronts. By
adding a component to the system that produces a wavefront that is the conjugate of the
measured deviations, the system can be made to produce a more diffraction-limited
wavefront and, thus, diffraction-limited performance (i.e., best possible performance).

15 [0003] Another example of an application where knowing the aberrations in a
wavefront is useful is in correcting human vision. For instance, as noted in U.S. Patent
No. 5,963,300, by measuring deviations from the perfectly spherical in reflections of laser
light from the eye of a patient, aberrations of the eye can be measured and, hence,
compensated for. In the '300 patent, light that is reflected from a patient's eye is passed
20 through two reticles, and the resulting moire shadow pattern is presented on a screen. An
imaging system images the shadow on the screen onto a camera, with subsequent
analysis being undertaken of the imaged shadow. The technique of the '300 patent is
based on geometrical or ray-tracing analysis, which as recognized herein requires
theoretical assumptions to perform the geometrical analysis that limit the amplitude of the
25 aberrations that can be measured as well as limit the accuracy with which the aberrations
can be measured.

[0004] Certain embodiments of the technology discussed below may provide
solutions to one or more of these drawbacks.

SUMMARY OF THE INVENTION

30 [0005] A system for determining aberrations in a coherent electromagnetic
wavefront includes a reticle that is positioned in the path of the wavefront, and a detector
also positioned in the path. In accordance with this aspect, the light detector is located at a
diffraction pattern self-imaging plane or Talbot plane relative to the reticle.

[0006] A processor may receive the output signal from the light detector and
35 determine aberrations in the beam based thereon. The aberrations in the beam may
represent aberrations in the wavefront due to the medium through which it passes, or an
object from which it reflects, or the source of the wavefront itself.

[0007] In a preferred, non-limiting embodiment, the processor executes logic that includes determining a phase gradient of the wavefront phase-front, and determining coefficients of polynomials based on the phase-front gradient which quantify the aberrations. The coefficients represent aberrations. Preferably, the gradient is obtained from a frequency domain transformation of the beam, wherein the gradient is the derivative of the phase of the wavefront in directions established by the reticle orientation. In a particularly preferred, non-limiting embodiment, the derivatives are determined in at least two directions, and the coefficients are determined by fitting derivatives of a set of known polynomials (such as e.g. Zernike polynomials) to the measured gradient.

10 [0008] In another aspect, a method for determining aberrations in an object includes passing a light beam from the object through a reticle, and then determining derivatives that are associated with the light beam subsequent to the light beam passing through the reticle. Using the derivatives, a measure of aberrations in the object can be output.

15 [0009] In yet another aspect, a computer program product includes a computer readable medium having a program of instructions stored thereon for causing a digital processing apparatus to execute method steps for determining aberrations in a wavefront. These method steps include representing a diffraction pattern produced by a wavefront, and determining directional derivatives of the representation. The derivatives are fit to known polynomials or derivatives thereof to obtain coefficients of polynomials. A wavefront characterization is provided based at least in part on the coefficients, with the wavefront characterization representing aberrations in the wavefront. A frequency domain representation of the image produced by the wavefront may also be generated. Furthermore, the directional derivatives may be determined in two directions.

25 [0010] In still another aspect, an apparatus for detecting aberrations in an object as manifested in a wavefront includes a reticle positioned in a path of the wavefront and a light detector positioned relative to the reticle to receive the diffracted self-image that is associated with the wavefront. The self-imaging distances are at discrete distances

from the reticle that are integral multiples of $d = \left(\frac{np^2}{\lambda} \right)$, where p is the period of the reticle and λ is the spectral wavelength of the wavefront. A processor receives signals from the light detector that represent the self-image. The processor derives the wavefront phase gradient associated with the wavefront and uses the coefficients of derivatives of polynomials that define the wavefront to determine the wavefront aberrations.

35 [0011] Another aspect of the invention comprises a system for determining the shape of an electromagnetic wavefront. This system includes at least one reticle

positioned in a path of the wavefront to be analyzed and at least one detector positioned to detect the wavefront passing through the reticle. The detector is substantially located at a diffraction pattern self-imaging plane relative to the reticle. The system further comprises at least one processor receiving an output signal from the light detector and calculating the shape of the wavefront based thereon.

[0012] Still another aspect of the invention comprises a method for determining aberrations in an optical system comprising at least one optical element. In this method, a test beam is propagated along a path with the optical system in the path of the test beam so as to be illuminated by the test beam. A reticle is inserted in the path of the test beam at a location with respect to the optical system so as to receive light from the optical system. The light propagates through the reticle. Directional derivatives associated with the light are determined subsequent to passing through the reticle. Additionally, the derivatives are used to output a measure of the aberrations.

[0013] Yet another aspect of the invention comprises a computer program product comprising a computer readable medium having a program of instructions stored thereon for causing a digital processing apparatus to execute method steps for determining aberrations in a wavefront. These method steps include representing at least a portion of an image produced by the wavefront and determining directional derivatives of the representation. In addition, directional derivatives are fit to known polynomials or derivatives thereof to obtain coefficients of polynomials. Furthermore, a wavefront characterization is provided based at least in part on the coefficients, the wavefront characterization representing aberrations in the wavefront.

[0014] Still another aspect of the invention comprises an apparatus for characterizing an object with a wavefront from the object. The apparatus includes at least one reticle positioned in a path of the wavefront and at least one light detector positioned relative to the reticle to receive a self-image diffraction pattern of the reticle produced by the wavefront. The apparatus further includes at least one processor receiving signals from the light detector representative of the self-image diffraction pattern and deriving derivatives associated therewith. The processor uses the derivatives to characterize the object.

[0015] Another aspect of the invention comprises a method for determining aberrations in a reflective or internally reflective object system. In this method, a light beam is passed from the object system through a reticle. This light beam produces a near field diffraction pattern at the Talbot plane. The method further comprises imaging the near field diffraction pattern at the Talbot plane and using the near field diffraction pattern to output a measure of aberrations in the light beam.

BRIEF DESCRIPTION OF THE DRAWINGS

[0016] The details of the various preferred embodiments, both as to their structure and operation, can best be understood in reference to the accompanying drawings, in which like reference numerals refer to like parts, and in which:

5 [0017] Figure 1 is a block diagram of the one preferred embodiment of a system architecture for measuring and characterizing a wavefront;

[0018] Figure 1a is a block diagram of another implementation of the system shown in Figure 1;

10 [0019] Figure 2 is a flow chart of a preferred method of characterizing the wavefront by propagating the wavefront through a pattern and imaging the pattern at the self-image plane;

[0020] Figures 3a-3c are schematic diagrams illustrating one method for converting the image produced at the self-image plane into gradient information corresponding to the wavefront at that self-image plane;

15 [0021] Figure 4 is a flow chart of preferred logic for data extraction in the spatial frequency domain; and

[0022] Figure 5 is a flow chart of further logic for extraction of the desired data from spatial frequency data.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

20 [0023] Referring initially to Figure 1, a wavefront sensor is shown, generally designated 10. As illustrated in Figure 1, a reference wavefront 11 can pass through (or, be reflected from) a system or element 12 (optical or otherwise). The system or element 12 can be an optics system, such as a telescope system, or it can be a human eye, or other object having properties, e.g., aberrations or curvature, sought to be measured.

25 [0024] As shown in Figure 1, a transferred wavefront 18, i.e., the wavefront 11 after having passed through or having been reflected from the system or element 12, passes through a reticle 20. For example, this reticle 20 may comprise without limitation, a diffraction grating, Ronchi ruling, or grid pattern. The reticle 20 diffracts the wavefront 18, and the diffracted wavefront self-images onto a sensor plane a self-imaging distance
30 "d" away from the reticle 20 at which location is disposed a light sensor 22 such as but not limited to a CCD or other detector array. The self-imaging distance "d" is dependent on the spectral wavelength of the coherent wavefront and the spatial frequency of the reticle. Preferably, the CCD is within about $\pm 10\%$ or about $\pm 20\%$ of one of the self-imaging planes in the near field diffraction region.

35 [0025] In a non-limiting, exemplary embodiment, the wavefront incident on the imaging detector can be represented by the following diffraction equation:

$$I(\vec{r}, z) = I_0 \cos\left(\frac{\pi \lambda z}{p^2}\right) \cos\left[\frac{2\pi}{p} (\vec{r} \cdot \hat{p} - \hat{r} \cdot (\vec{z} \times \vec{\nabla} w))\right]$$

(1)

where: λ is the wavelength of the coherent wavefront, z is the propagation distance with the associated vector \vec{z} in propagation direction, p is the period of the reticle (distance from the beginning of one grid line to the next grid line), r is the spatial dimension in the plane of the detector with its associated vector \vec{r} , \hat{p} is the corresponding unit vector, \hat{p} the unit vector representing the reticle orientation, and ∇ is the directional—derivative (or, gradient) of the wavefront phase “ w ” that is being measured. The self-imaging distance is dependent on the spectral wavelength of the coherent wavefront and the spatial frequency of the reticle and is given by:

$$d = \left(\frac{np^2}{\lambda} \right)$$

(2) where n is the integer multiple at which distances the self-images occurs. For example, for a reticle having a grating spacing, p , of 50 micrometers (μm), this distance, d , may be between about 2.9 to 3.0 millimeters (mm) or in proximity thereto for light having a wavelength of 850 nanometers (nm). Integer multiples of this distance may be appropriate as well.

[0026] As described below, this reticle 20 may comprise rulings in orthogonal x and y directions having substantially the same period p . In other embodiments, the spacing p_x and p_y of the orthogonal rulings may be different for the x and y directions. Corresponding self-image planes at distances d_x and d_y for the different directed rulings may result. Similarly, use of more than one or two reticle patterns superimposed on another having same or different periodicity are considered possible.

[0027] The self-imaged reticle on the light sensor or detector 22 that is located at the self-image plane contains the desired information pertaining to the phase characteristics of the coherent wavefront. This information is extracted from the spatial signal collected at the sensor 22 and sent to a data processor (i.e., computer) 24 for processing in accordance with the disclosure below. To undertake the logic, the processor 24 accesses a preferably software-implemented module 26, and outputs a signal representative of the wavefront (or a conjugate thereof) to an output device 28, such as but not limited to a printer, monitor, computer, network, or other appropriate device.

[0028] In various embodiments, the beam that emerges from the reticle 20 establishes a diffraction pattern. This pattern, however, substantially cannot be discerned except at the self-image planes that are spaced integer multiples of a distance “ d ” from the reticle 20, as discussed above. Thus, the self image diffraction pattern can be detected by

the light sensor or detector 22 that in one preferred embodiment is placed at the first ($n=1$) self-image plane as shown in Figure 1, although it is to be understood that the sensor or detector 22 can be positioned at any of the self-image planes that are spaced from the reticle 20 by integer multiples of the distance "d".

5 **[0029]** Logic may be executed on the architecture shown in Figure 1 in accordance with processes and methods described and shown herein. These methods and processes include, but are not limited to, those depicted in at least some of the blocks in the flow chart of Figure 2 as well as the schematic representations in Figures 3a-3c and flow charts in Figures 4 and 5. These and other representations of the methods and
10 processes described herein illustrate the structure of the logic of various embodiments of the present invention which may be embodied in computer program software. Moreover, those skilled in the art will appreciate that the flow charts and description included herein illustrate the structures of logic elements, such as computer program code elements or electronic logic circuits. Manifestly, various embodiments include a machine component
15 that renders the logic elements in a form that instructs a digital processing apparatus (that is, a computer, controller, processor, etc.) to perform a sequence of function steps corresponding to those shown.

[0030] In other words, the logic may be embodied by a computer program that is executed by the processor 24 as a series of computer- or control element-executable
20 instructions. These instructions may reside, for example, in RAM or on a hard drive or optical drive, or the instructions may be stored on magnetic tape, electronic read-only memory, or other appropriate data storage device that can be dynamically changed or updated.

[0031] Figure 1a shows a particular non-limiting implementation of the system
25 10 in which the electromagnetic energy is reflected from an object or is internally reflected from within an object. Examples of applications include microwave topography of large surfaces, wherein the electromagnetic energy is microwave and the object is the surface sought to be measured; optical topography of reflective surfaces, wherein the electromagnetic energy is laser light; retinal reflection within an eye in order to measure
30 the aberrations of the eye, and gamma ray reflection within very small objects in order to characterize mechanical or optical properties.

[0032] Accordingly, for illustration purposes Figure 1a shows that the reference wavefront 11 passes through (or, is reflected from) a transfer (optical or otherwise) system or element 15, such as but not limited to a beamsplitter, along a propagation path 13. The
35 wavefront 11 is incident on an object 12 such as a human eye wherein it is either reflected externally or transmits into the object 12 where it is internally reflected. The return wavefront follows along a return path 17, and can be reflected from or transmitted through

the transfer system or element 15. The wavefront may then pass through an optical relay system 19. The transferred wavefront 18 passes through the reticle 20 and is processed as described above in reference to Figure 1.

5 **[0033]** The logic of the processor 24 can be appreciated in reference to Figure 2. Commencing at block 30 in Figure 2, the wavefront 18 of the beam passes through the reticle 20. Diffraction effects cause a self-image of the reticle to appear at the self-image planes described above, including at the first plane located at a distance "d" from the reticle 20 where the detector 22 is positioned. The particular plane chosen for the position of the detector 22 preferably has sufficient resolution cells to resolve the diffraction pattern.

10 **[0034]** The self-image diffraction pattern caused by the beam 18 passing through the reticle 20 is acquired at block 33 by the sensor or detector 22 and is represented by the signal output by the light detector 22, as received by the processor 24. Proceeding to block 34, the signal in the spatial image domain is transformed to the spatial frequency domain. In one non-limiting embodiment, executing a Fast Fourier Transform
15 (FFT) on the signal performs this, although it is to be understood that other mathematical transformations can be used. While Figure 2 indicates that the FFT is implemented in software, it is to be understood by those skilled in the art that alternatively, prior to being sent to the processor 24 an optical FFT of the return beam can be made using optics such as are known in the art.

20 **[0035]** Proceeding to block 36, regions of interest in the frequency domain may be selected based on the reticle period, illumination (i.e., wavelength), and other factors discussed further below. This selection can be a priori, and need not be undertaken during measurement. Essentially, at block 36 the regions of interest for which the gradient (directional derivative) of the wavefront is to be determined are located in the spatial
25 frequency domain and isolated.

[0036] In various preferred embodiments, the portions of the spatial frequency domain that contain the slope information and that consequently are isolated depend on the configuration of the reticle 22 and can be, e.g., represented by distributions mapped on different places on orthogonal axes in frequency space. Suitable spatial frequency domain
30 manipulation is further illustrated in Figure 3, discussed below.

[0037] Proceeding to block 38, an inverse transform is applied only to the isolated frequency space regions of the signal to render a spatial representation of the gradient of the wavefront preferably in the direction normal to the linear or segmented linear dimension of the reticle. Thus, if the reticle contains a singular set of linear grating
35 lines, there will be two regions of the spatial frequency domain containing the desired information. If there are two sets of linear gratings superimposed in the reticle, the spatial frequency domain will contain four regions of interest. Each additional set of linear

gratings provides more information pertaining to the wavefront gradient. In the limit, a circular grating reticle represents an infinite number of segmented linear gratings superimposed on each other. Preferably, the reticle contains two orthogonal superimposed linear grating patterns. In a non-limiting preferred embodiment, the wavefront gradient is determined in isolated regions in two directions. In a non-limiting example, when the object 12 is a human eye, the two directions are orthogonal to each other and lie in a plane defined by the front of and tangential to the patient's eye, with one of the directions extending from the center of the eye at a 45° angle relative to the horizontal and tangent to the eye when the, patient is standing and facing directly forward.

5 [0038] If desired, in a non-limiting embodiment filtering of random background noise can be further applied by using a "computationally-implemented" matte screen by which the spatial characteristics of the self-image are enhanced and the background reduced to very low (e.g., approximately zero) frequency components in the spatial frequency domain. This principle will be further discussed in relation to Figure 5.

15 [0039] Moving to block 40, a set of known functions such as polynomials (and their derivatives) is defined or otherwise accessed for the two directions mentioned above. These polynomials can be used to model the wavefront. In one preferred, non-limiting embodiment, a set of 36 Zernike polynomials are used. Then, at block 42 the derivatives of the known polynomials are fit to the derivatives (i.e., gradient) determined at block 38 using, e.g., a least squares fit or other fitting algorithm.

20 [0040] The outcome of the fitting step at block 42 is that each polynomial has an accompanying coefficient, also referred to as the "amplitude" of the polynomial. Each coefficient represents an aberration from the perfectly spherical in the return beam 18 and, hence, an aberration in the object 12. Consequently, at block 44 a reconstructed wavefront equation can be output (to, e.g., the output device 28) that is the set of the known polynomials with the coefficients obtained in the fitting step at block 42. At block 46, the output, and in particular the coefficients in the reconstructed wavefront equation, can be used to indicate aberrations in the original wavefront and, hence, in the object 12. Furthermore, the output can be used as a basis for implementing corrective optics for the system 12 that essentially represent the conjugate of the polynomials and/or coefficients to reduce or null out the aberrations of the object 12.

25 [0041] A schematic representation of an exemplary process for characterizing a wavefront gradient is depicted in Figures 3a-3c. A spatial image 100 of the reticle at the detector located in the self-image plane is converted by applying a Fourier transform, represented by block 102, into spatial frequency data 104. The result, is a spatial frequency pattern that includes four regions of interest 106a, 106b, 106c, and 106d which may correspond to a set of first order components in frequency space. These four regions

comprise point spread functions (PSF) displaced from the origin of the spatial frequency map in directions corresponding to $\pm f_x$ and $\pm f_y$. As shown in block 108, one of these four regions is selected. In Figure 3b, the point spread function at the $(+f_{x0}, 0)$ location is selected and the inverse Fourier transform is performed on this spatial frequency distribution as represented by block 110. In this manner, the gradient along the x direction of the wavefront at the self-image plane can be obtained as shown indicated by block 112. Similarly, Figure 3c shows the point spread function at the $(0, +f_{y0})$ position in block 114. The inverse Fourier transform is performed on this point spread function as represented by block 116 to obtain the gradient of the wavefront in the y direction shown in block 118.

10 **[0042]** Figure 4 shows further details of this process as discussed with respect to blocks 34, 36 and 38 in Figure 2. At block 50 in Figure 4, the self-image of the reticle is converted using software or optically from spatial data to spatial frequency data. As discussed above, this is preferably performed with a Fourier Transform algorithm and preferably a Fast Fourier Transform computer software algorithm (FFT). Moving to block 15 52, from an a priori knowledge of the system 10 configuration, regions of interest in the spatial frequency domain are selected. The a priori information is provided at block 54 as follows. The reticle 20 has (a) periodic pattern(s) in known directions. The period of the reticle, the number of superimposed reticles, and the spatial orientations of the reticle relative to the wavefront path of propagation can be used to locate these regions. 20 Gradient data in the individual regions of interest is accessed at block 56 and isolated at block 58. This data has symmetry in the spatial frequency domain. Accordingly, in block 60 if desired only one of the symmetric data sets need be selected. Then in block 62 each set is converted back to the spatial domain. The offset of the location in frequency space of the "first order" region of interest may be used to calibrate the gradient information. This 25 process of obtaining the wavefront phase gradient information is included in block 38 in Figure 2.

[0043] Without subscribing to any particular scientific theories, the above operations by which the wavefront is extracted from equation (1) can be expressed in analytical form as follows. First, the non-limiting Fourier transform on the wavefront 30 executed at block 50 in Figure 4 can be expressed as

$$F\{l(r,z)\} \begin{matrix} f^2_{x,y} & f^4_{x,y} \\ f^1_{x,y} & f^3_{x,y} \end{matrix} \Rightarrow F(\nabla w)$$

(3) wherein the notation $f^1_{x,y}$, $f^2_{x,y}$, $f^3_{x,y}$, $f^4_{x,y}$ indicates that in certain embodiments described above such as illustrated in FIGURES 3a-3c, the relevant frequency information obtained by the Fourier transform is contained in four first order

distributions or point spread functions 106a, 106b, 106c, 106d located in four sectors in frequency space. Similarly, the two spatial frequency regions $f_{x,y}^1$ to $f_{x,y}^2$ and $f_{x,y}^3$ to $f_{x,y}^4$ are the two dimensional areas in the frequency domain that contain the relevant data, and $F(\nabla w)$ represents the received wavefront. The location of the point spread function may vary in different embodiments.

[0044] Then, the gradient (∇w) of the wavefront is determined by performing the inverse Fourier transform (F^{-1}) on equation (3) as follows:

$$F^{-1}\{F(\nabla w)\} \Rightarrow \nabla w . \quad (4)$$

Next, the set of partial derivatives, or gradients, of the chosen polynomial set, e.g., Zernike polynomials (∇Z , or Z_x and Z_y) are made to best approximate the gradient of the phase front (∇w) via one or more fitting algorithms such as for example a least squares algorithm. That is,

$$\nabla w = \sum_{i=1}^n A_i \nabla Z_i , \quad (5)$$

where, n is the number of polynomials chosen to best approximate the wavefront phase gradient, and A_i is the coefficient, or amplitude, of the polynomial Z_i . The wavefront phase "w" can now be described as follows:

$$w = \sum_{i=1}^n A_i Z_i . \quad (6)$$

The aberrations in the wavefront can be described by the values of the coefficients A_i .

[0045] The flow chart of Figure 5 shows the process of the "computationally-implemented" matte screen discussed above in relation to Figure 2. In a monochromatic system a high pass spectral filter may be used to eliminate signal noise. In one exemplary embodiment, this filter is a piece of hardware called a matte screen. In many applications a matte screen is not practical to integrate into the system. Accordingly, the matte screen can be computationally implemented on the self-images.

[0046] The contrast of the image and the self-image fundamental spatial frequency are respectively received from blocks 70 and 71 and input to block 72, where the two inputs are compared to discriminate the self-image signal. If the contrast from block 70 is lower than the fundamental spatial frequency from block 71, the matte screen is implemented within block 34 of Figure 2, with the location of the peak value in the region of interest in block 38 providing the fundamental (predominant) frequency within the self-image signal. From the peak, a finite impulse response (FIR) kernel is derived at block 74 that functions as a high-pass filter of spatial frequency data. Only frequencies higher than

the designed limit will remain in the signal, and all others are eliminated at block 76 by mathematically convolving the kernel with the self-image signal.

- 5 **[0047]** By employing methods such as described above, a mathematical representation of the wavefront and of the aberrations can be obtained. Additionally, conjugate structures, e.g., conjugate optics, can be created to substantially offset or cancel the aberrations in the wavefront. In the case, for example, where the wavefront in the eye is measured, these conjugate optics, e.g., may take the form of a corrective lens and the method of measuring the wavefront described above can be employed to determine the appropriate prescription for such a lens.
- 10 **[0048]** Those skilled in the art will appreciate that the methods and designs described above have additional applications and that the relevant applications are not limited to those specifically recited above. Also, the present invention may be embodied in other specific forms without departing from the essential characteristics as described herein. The embodiments described above are to be considered in all respects as
- 15 illustrative only and not restrictive in any manner.

WHAT IS CLAIMED IS:

1. A system for determining the shape of an electromagnetic wavefront, comprising:

at least one reticle positioned in a path of the wavefront to be analyzed;

5 at least one detector positioned to detect the wavefront passing through the reticle, the detector being substantially located at a diffraction pattern self-imaging plane relative to the reticle; and

at least one processor receiving an output signal from the light detector and calculating the shape of the wavefront based thereon.

10 2. The system of Claim 1, wherein the location of the self-imaging plane is a function of the wavelength of the wavefront and the spatial periodicity of the reticle.

3. The system of Claim 1, wherein said reticle comprises a grating having a grating spacing, p .

4. The system of Claim 2, wherein said diffraction pattern self-imaging plane is
15 located in the near field a longitudinal distance of approximately $d = \left(\frac{np^2}{\lambda} \right)$ from said reticle, wherein p is the grating spacing of the grating, λ is the spectral wavelength of the wavefront, and n is an integer.

5. The system of Claim 1, wherein said reticle comprises a grating having a grid-like pattern.

20 6. The system of Claim 1, wherein the processor executes logic to undertake method acts comprising:

determining directional derivatives of the electromagnetic wavefront.

7. The system of Claim 6, wherein the method acts further include transforming a diffraction pattern of the wavefront at the detector from a spatial image
25 domain into a spatial frequency domain, prior to the act of determining coefficients.

8. The system of Claim 7, wherein selected portions in the spatial frequency domain are used to determine said coefficients.

9. The system of Claim 6, wherein the method acts include determining coefficients of polynomials based on at least one gradient of a phase-front of the
30 wavefront, the coefficients being representative of the shape of the wavefront.

10. The system of Claim 9, wherein the coefficients are determined by fitting derivative functions of a set of known polynomials to the derivatives obtained during the determining act.

35 11. The system of Claim 6, wherein directional derivatives are determined in at least two directions.

12. The system of Claim 6, wherein said method acts further comprise implementing a computational matte screen for filtering out noise.

13. A method for determining aberrations in an optical system comprising at least one optical element, said method comprising:

5 propagating a test beam along a path with said optical system in said path of said test beam so as to be illuminated by said test beam,

inserting a reticle in said path of said test beam at a location with respect to said optical system so as to receive light from said optical system, said light propagating through said reticle;

10 determining directional derivatives associated with said light subsequent to passing through the reticle; and

using the derivatives to output a measure of said aberrations.

14. The method of Claim 13, further comprising transforming a diffraction pattern produced by said light passing through said reticle from a spatial image into a spatial frequency distribution.

15. The method of Claim 13, further comprising determining coefficients of polynomials based on the directional derivatives.

16. The method of Claim 15, wherein the coefficients are determined by fitting derivatives of a set of known polynomials to data obtained during the determining act.

20 17. The method of Claim 13, comprising determining directional derivatives in at least two directions.

18. The method of Claim 13, comprising locating a light detector at a position in said path so as to receive a self-image of the reticle.

25 19. The method of Claim 13, further comprising implementing a computational matte screen as a filter.

20. A computer program product, comprising:

a computer readable medium having a program of instructions stored thereon for causing a digital processing apparatus to execute method steps for determining aberrations in a wavefront, comprising:

30 representing at least a portion of an image produced by said wavefront;

determining directional derivatives of the representation;

fitting the directional derivatives to known polynomials or derivatives thereof to obtain coefficients of polynomials; and

35 providing a wavefront characterization based at least in part on the coefficients, the wavefront characterization representing aberrations in the wavefront.

21. The program product of Claim 20, further comprising:
generating a frequency domain representation of the wavefront.
22. The program product of Claim 21, wherein the directional derivatives are determined in two directions.
- 5 23. An apparatus for characterizing an object with a wavefront from the object, comprising:
at least one reticle positioned in a path of the wavefront;
at least one light detector positioned relative to the reticle to receive a self-image diffraction pattern of the reticle produced by the wavefront; and
10 at least one processor receiving signals from the light detector representative of the self-image diffraction pattern and deriving derivatives associated therewith, the processor using the derivatives to characterize said object.
24. The apparatus of Claim 23, wherein the object is an eye.
- 15 25. The apparatus of Claim 23, wherein the location of the reticle is related to the wavelength of the wavefront and spatial frequency of the reticle.
26. The apparatus of Claim 23, wherein the processor produces frequency transformation of the wavefront to produce a distribution in frequency space and derives derivatives of phases of the wavefront from the distribution in frequency space.
- 20 27. The apparatus of Claim 23, wherein the processor determines derivatives of phases in two directions.
28. The apparatus of Claim 23, wherein the processor fits a set of known derivatives to the derivatives determined by the processor to obtain coefficients of polynomials representative of the aberrations.
- 25 29. A method for determining aberrations in a reflective or internally reflective object system, comprising:
passing a light beam from the object system through a reticle, said light beam producing a near field diffraction pattern at said Talbot plane;
imaging said near field diffraction pattern at said Talbot plane;
30 using said near field diffraction pattern to output a measure of aberrations in the light beam.
30. The method of Claim 29, wherein the object system is an eye and said method is for determining aberration in said eye.
31. The method of Claim 29, further comprising transforming a wavefront
35 associated with the light beam from a spatial image domain into a spatial frequency domain.

32. The method of Claim 31, wherein only selected portions in said spatial frequency domain are used to determine coefficients.

33. The method of Claim 29, comprising locating a light detector at said Talbot plane to detect the near field diffraction pattern.

5 34. The method of Claim 29, further comprising designing corrective optics based on said measure of aberrations in said light beam so as to reduce said aberrations.

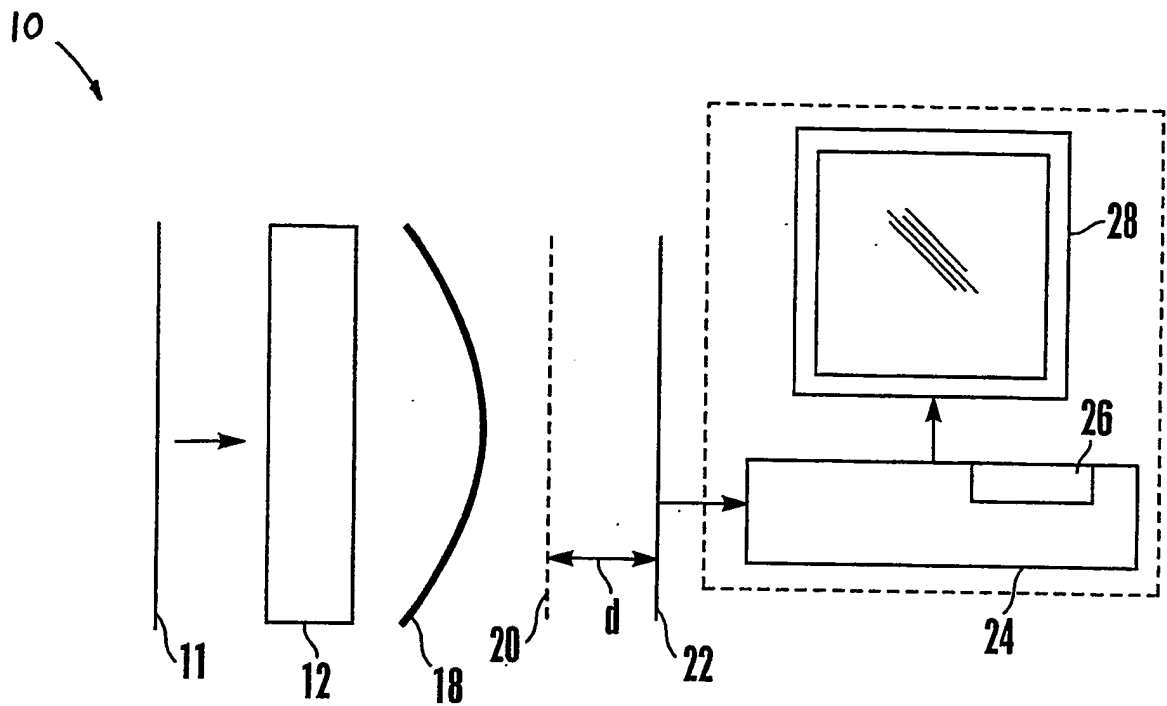


Fig. 1

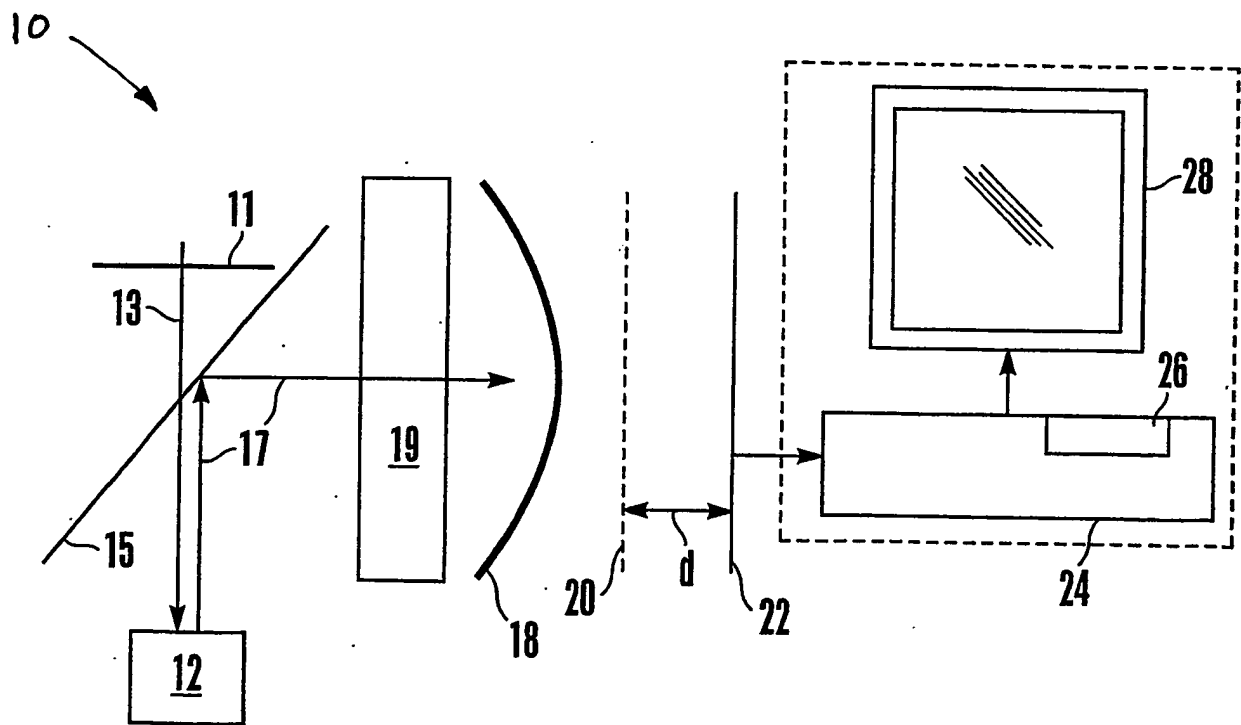
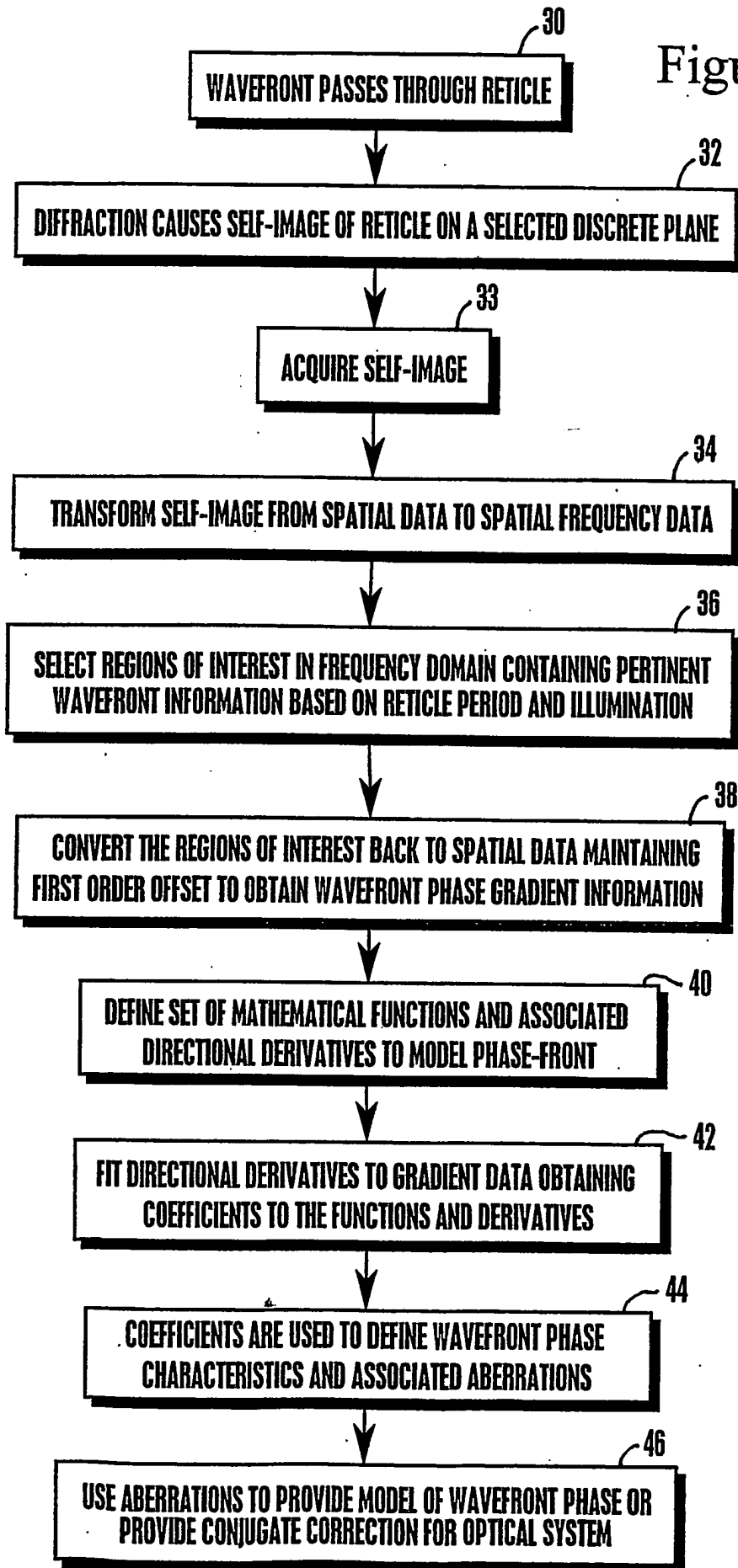


Fig. 1a

Figure 2



BEST AVAILABLE COPY

FIG. 3a

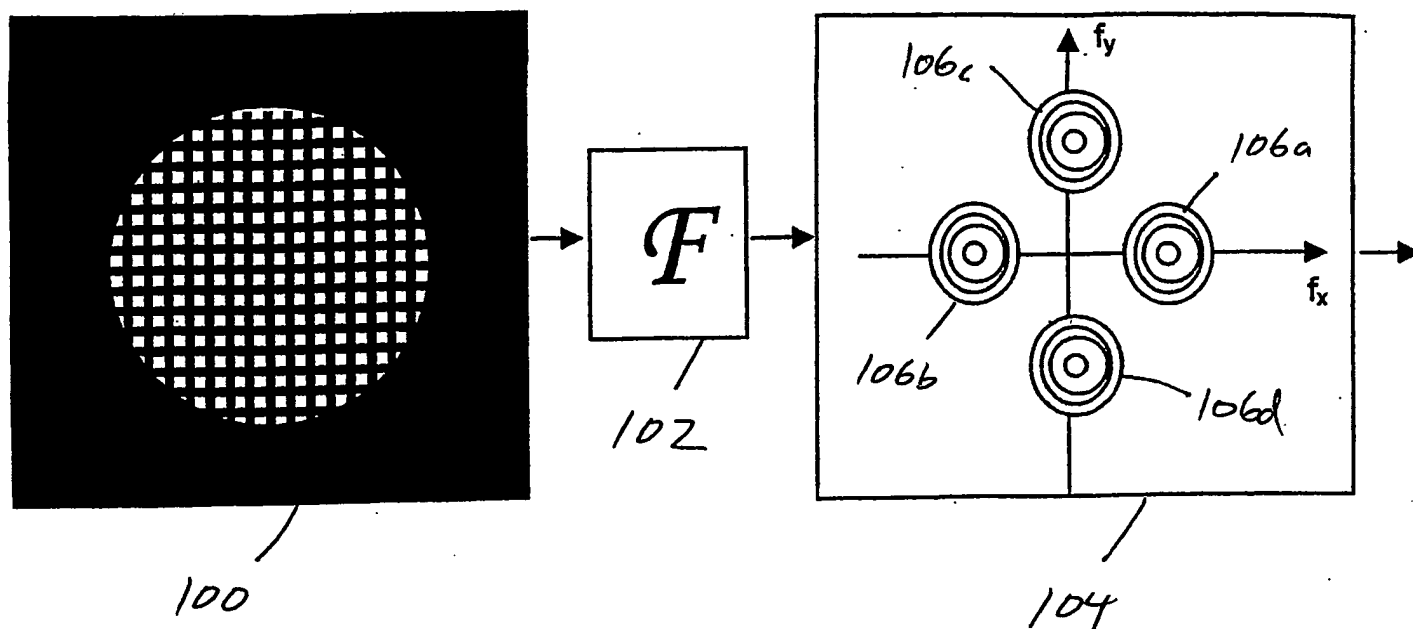


FIG. 3b

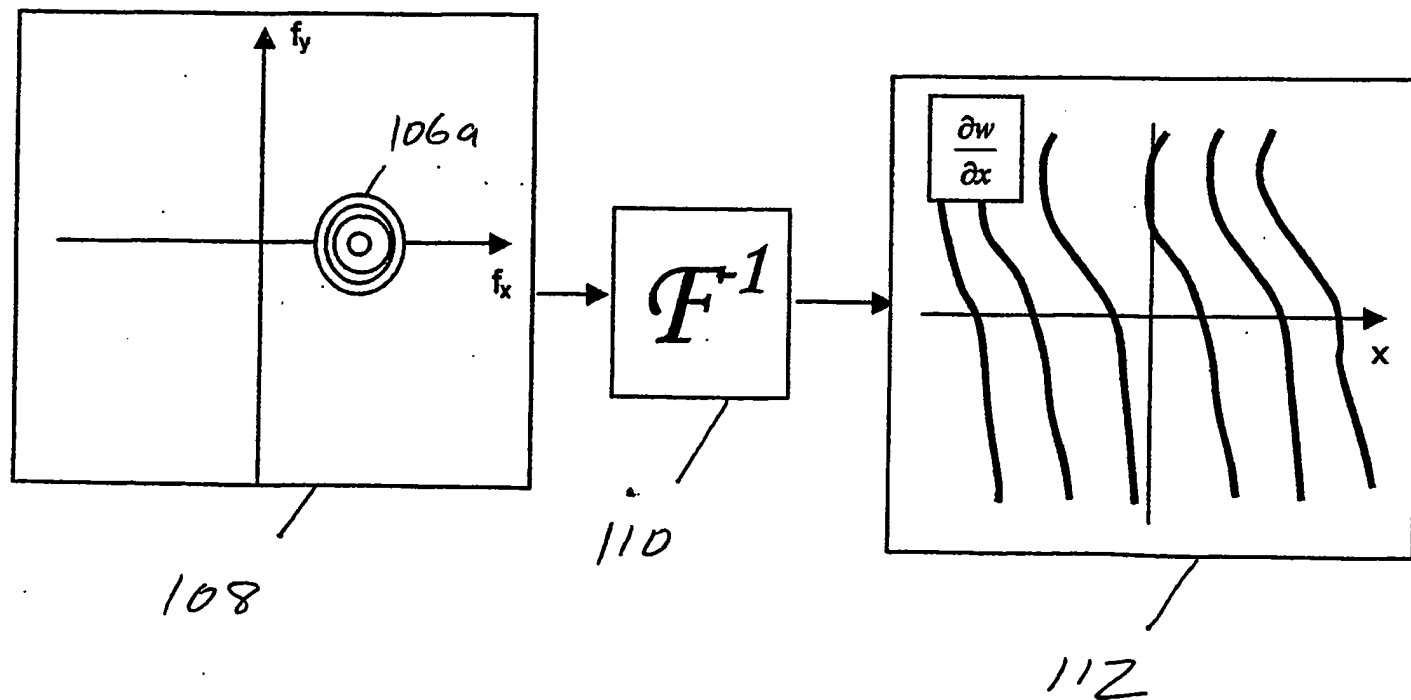
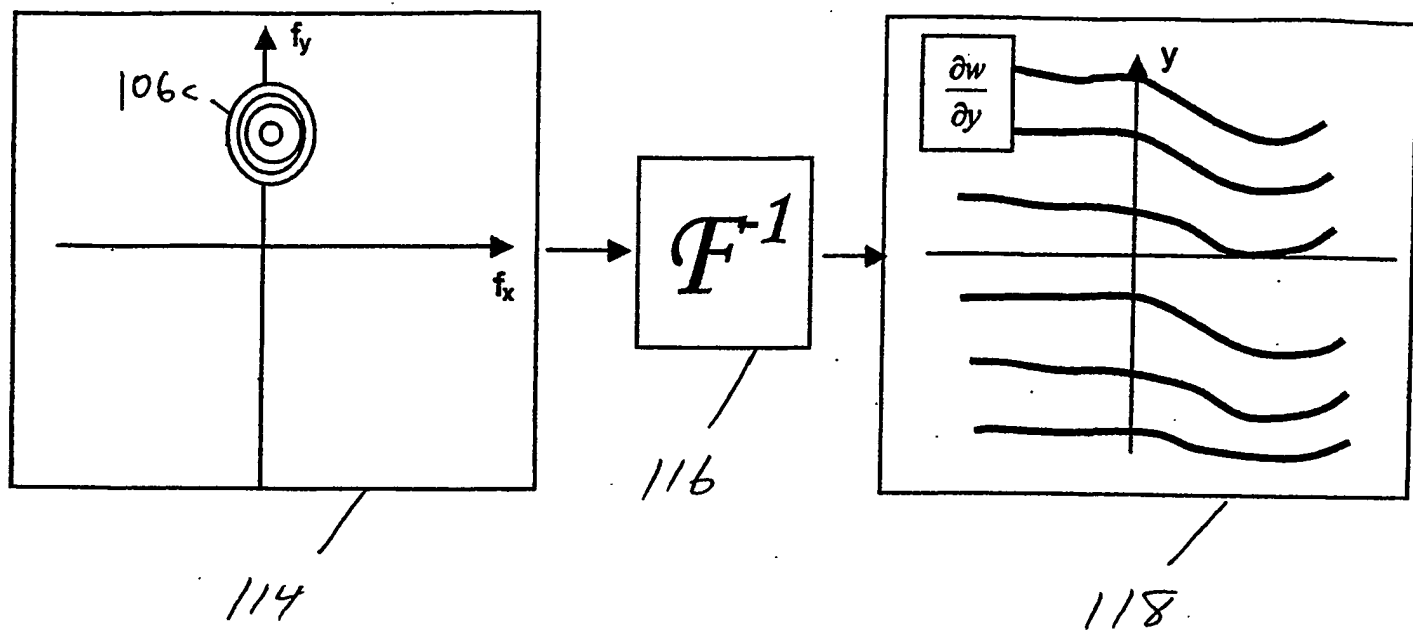
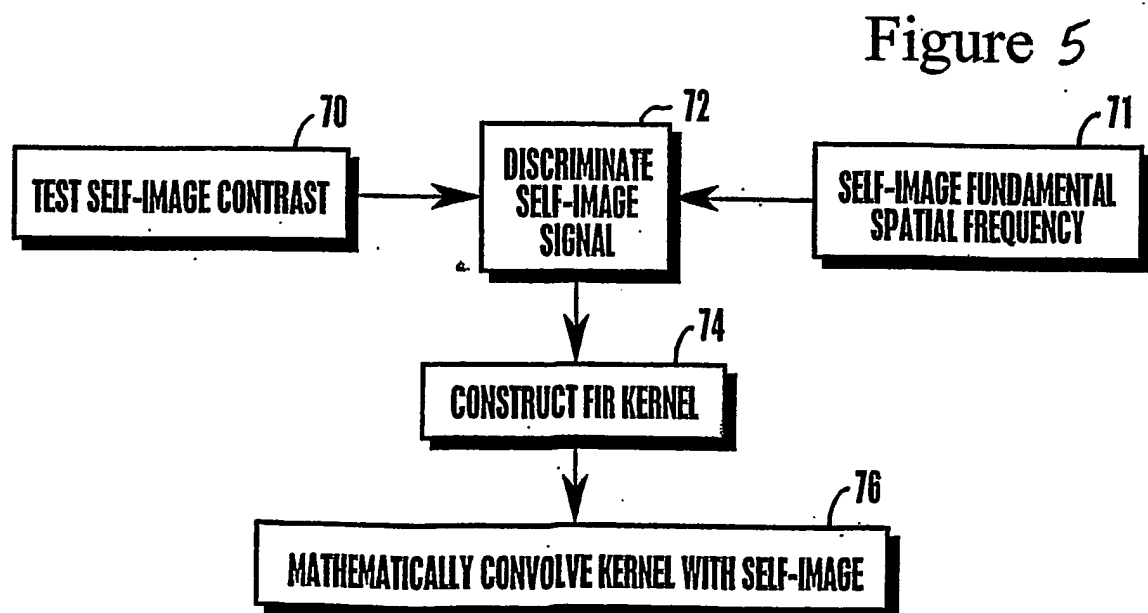
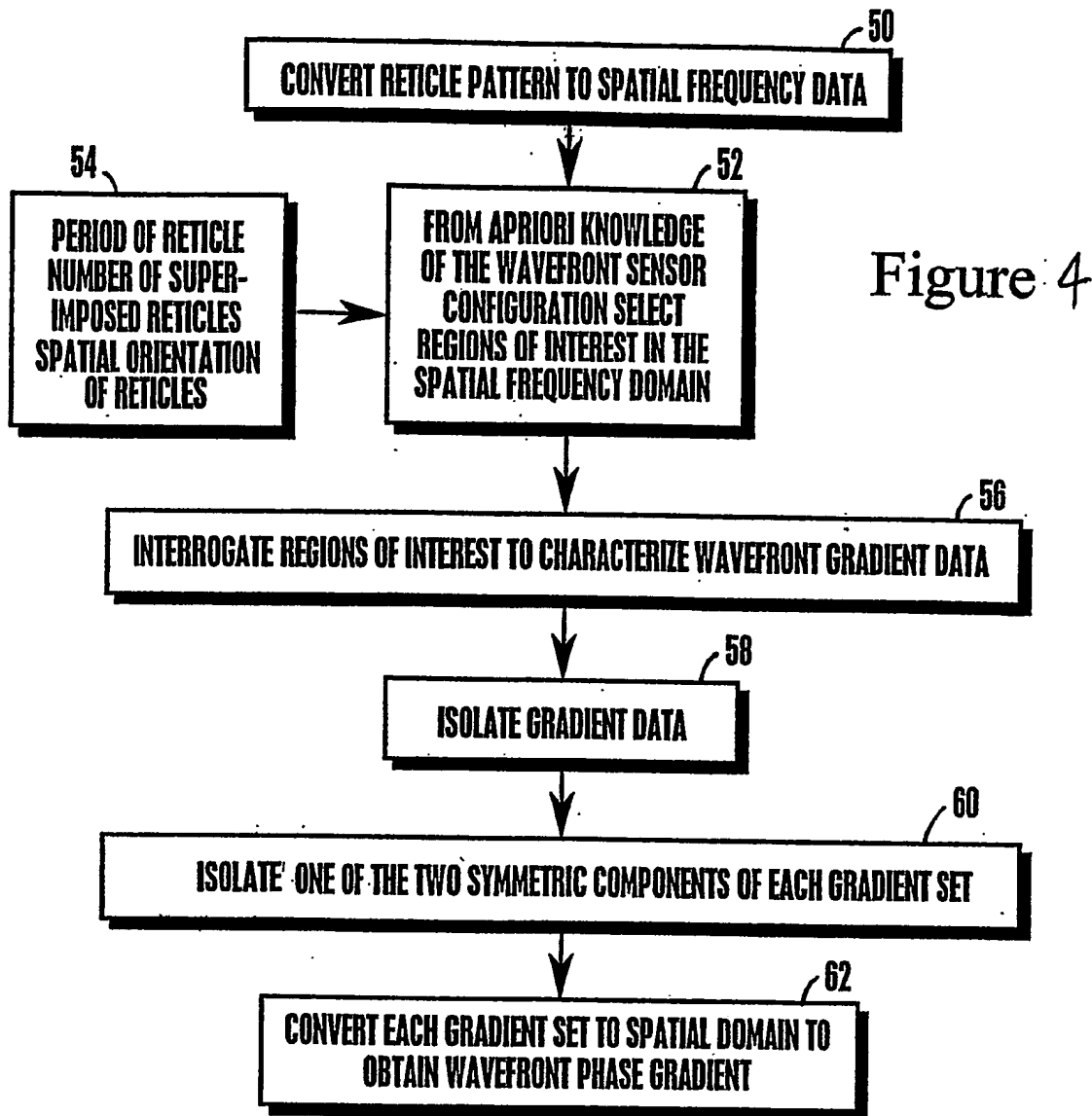


FIG. 3c





INTERNATIONAL SEARCH REPORT

International application No.

PCT/US02/39526

A. CLASSIFICATION OF SUBJECT MATTER

IPC(7) : G01B 9/00

US CL : 356/124

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 356/124-127; 351/205-221

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
east search

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
search terms: reticle, derivative, gradient, grating, diffraction

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X — A	US 5,963,300 A (HORWITZ) 05 October 1999 (05.10.1999), figure 1.	1-8, 12-14, 18-19, 23-26 and 29-34 9-11, 15-17, 20-21 and 27-28

☐ Further documents are listed in the continuation of Box C.

☐ See patent family annex.

Special categories of cited documents:	
"A" document defining the general state of the art which is not considered to be of particular relevance	"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"E" earlier application or patent published on or after the international filing date	"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"O" document referring to an oral disclosure, use, exhibition or other means	"&" document member of the same patent family
"P" document published prior to the international filing date but later than the priority date claimed	

Date of the actual completion of the international search

06 March 2003 (06.03.2003)

Date of mailing of the international search report

28 MAR 2003

Name and mailing address of the ISA/US

Commissioner of Patents and Trademarks

Box PCT

Washington, D.C. 20231

Facsimile No. (703)305-3230

Authorized officer

Frank Font

Telephone No. (703) 305-0956

Deborah P. Vega
Deborah P. Vega
Paralegal Specialist

Technology Center 2800
(703) 308-3078